Challenge of polarized beams at future colliders

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Abstract. A short overview about the potential of polarized beams at future colliders is given. In particular the baseline design for polarized beams at the ILC is presented and the physics case for polarized e^- and e^+ is discussed. In order to fulfil the precision requirements spin tracking from the source to the interaction point is needed. Updates concerning the theoretical calculations as well as their implementation in simulation codes are reported.

1. Introduction

1.1. Overview about colliders with polarized beams

As shown in past particle physics experiments, beam polarization is a very powerful tool to achieve physics goals and optimize results. The great success of the SLD experiments at the e^+e^- collider SLC with the best single measurement of the electroweak mixing angle, $\sin^2\theta_{\rm eff} = 0.23098 \pm 0.00026$ [1], was due to the application of polarized e^- beams with about $P_{e^-} = 78\%$. Although the LEP e^+e^- experiment had much higher luminosity, a larger statistical uncertainty, $\sin^2\theta_{\rm eff} = 0.23221 \pm 0.00029$, was derived. The polarization of the beams at LEP caused by the Sokolov-Ternov effect was very small and could not be exploited for physics analyses, but was nevertheless very useful for calibrating the energy of the beams [2]. Polarization at HERA, the asymmetric circular ep-collider, reached a polarization of $P_{e^\pm} = 40\%$ to 50% at low background in the colliding mode (about 70% in non-colliding mode) and was used to test the non-existence of right-handed charged currents [3].

Many of the designs of future colliders also foresee the option of polarized beams. For instance, future upgrades of ep colliders, i.e. eRHIC [4] and LHeC [5], may include this option in order to have access to the spin structure of the gluons. The most prominent future collider with polarized beams is the e^+e^- International Linear Collider (ILC), which is already in the engineering phase of its design. An electron beam with a polarization between 80% and 90% is included in the baseline design: using the same scheme for producing polarized electrons as was already successfully demonstrated at the SLC. Furthermore the baseline e^+ source, based on undulator radiation [6], generates polarized e^+ with high luminosity and a predicted polarization

of about 30%. The degree of the polarization can easily be upgraded to about 60% [7]. The option of using polarized e^- and e^+ beams at CLIC, a future multi-TeV collider, is also being considered as part of the current design studies [8].

1.2. Physics motivation for polarized beams at the ILC
Polarizing both beams at the linear collider instead of only the e^- beam has several advantages: improving statistics, enhancing rates and cross sections and suppressing background processes. Furthermore there exist several examples were having both beams polarized is mandatory, for instance, in order to determine specific quantum numbers of new particles. The polarization of both beams is also needed to achieve the ultimate precision predicted for the measurements at GigaZ. The physics case and the need of polarized e^- and e^+ has been established and quantified [9].

A striking feature of the current ILC design is that it provides without any upgrades an e^+ polarization of about 30%. Numerous questions could already be addressed with such an amount of polarization. In many cases polarized beams with $(P_{e^-}, P_{e^+}) = (80\%, 30\%)$ lead to already half of the physics gain that could be achieved with $(80\%, 60\%)$. These gains could not be achieved by using higher electron polarization alone, not even with 100% e^- beam polarization [9, 10].

2. Schemes for polarizing beams at the linear collider
The electron source consists of a circularly polarized high-power laser beam and a high-voltage DC gun with a semiconductor photocathode. For the positron source a scheme, based on helical-undulator radiation, has been chosen as the most reliable solution for producing the required flux of order 10^{14} positrons per pulse (for details see [7, 11]). The design produces positrons via an electromagnetic shower instigated in a thin target by incident circularly polarized synchrotron radiation produced by the undulator operating on the main ILC e^- beam. The undulator-based source produces 1.5 positrons per an electron in the main linac as required to guarantee smooth operation of the ILC, and imposes much less demands for capture issues and damping ring acceptance than conventional technologies. This method has been experimentally tested in the E166 experiment at SLAC [12] and several prototypes for the ILC-type undulator have already been successfully tested (for details see [13]). Studies and simulations show that the undulator-based source has negligible impact on the emittance and on the energy spread of the e^- beam [13]. The undulator-based e^+ source leads to much less radiation damage at the target: for instance, it causes less activation (dose rate) by a factor of about 70 (25) and produces less neutrons by about a factor of 10 compared with the target at a conventional source [14]. Concerning the status of prototype targets for the ILC, see [15].

The successful accomplishment of the experiment E166 led to the inclusion of polarization in the physics simulation program GEANT4 [16]. This is important for physics analyses at all future colliders, and an updated version of the program is now publically available [17]. This polarization extension is now being used in several simulation studies around the polarized positron source, for instance, for the design and optimization of a low-energy positron polarimeter [18].

An alternative scheme for the inclusion of polarized e^+ beams at the linear collider is based on laser-Compton-backscattering. Prototypes for this scheme have been successfully tested at ATF [19]. Several applications of this scheme to future accelerators have been discussed including SuperB factories, a possible multi-TeV design for a future linear collider CLIC, and energy-recovery linacs (ERL).

3. Spin tracking from source to the interaction point
It is important to ensure that no significant polarization is lost during the transport of the e^- and e^+ beams from their sources to the interaction region. The largest effects are expected to

be caused by the collision of the two beams at the interaction point [20]. Transport elements downstream of the sources which can contribute to a loss of polarization include the initial acceleration structures, transport lines to the damping rings, the damping rings, the spin rotators [21], the main linacs, and the high energy beam delivery systems; as overview, for instance, see [22].

3.1. Beam-beam interactions

The main sources of depolarization effects during beam-beam interactions are the spin precession and the spin-flip processes, i.e. the Sokolov-Ternov (S-T) effect. Usually the spin precession effect is dominant, but at higher energy the depolarization due to the S-T effect increases [23]. Spin precession is described by the Thomas–Bargman-Michel-Telegdi (T-BMT) equation,

$$\frac{\mathrm{d}\vec{S}}{dt} = -\frac{e}{m\gamma}[(\gamma a + 1)\vec{B}_T + (a+1)\vec{B}_L - \gamma(a + \frac{1}{\gamma+1})\beta\vec{e}_v \times \frac{\vec{E}}{c}] \times \vec{S}, \tag{1}$$

where a describes the anomalous magnetic moment of the electron given by the higher-order corrections to the $ee\gamma$ vertex. In the environment of strong colliding beams, however, the usual perturbation theory cannot be applied. Therefore modified expressions for the anomalous magnetic moment in a medium have been derived [24]. These expressions have been evaluated in the no-scattering case, using the quasi-classical approximation that implies that the momentum change due to the strong fields occurs slowly on the scale of the particle wavelength. This condition is fulfilled if the Larmor radius of the particle due to the existing magnetic field in the bunches is much larger than the particle wavelength. It has been checked that even in the strong field environment of the ILC such a quasi-classical approximation can be used and the modified T-BMT equation can be applied to describe the spin precession sufficiently accurately, see also [24, 25, 26].

The production of incoherent background pairs [27] is strongly dependent on the polarization state of the initial photons involved in the process [28]. These photons are either real (beamstrahlung) or virtual and depend on the electromagnetic field of the oncoming beam. The CAIN [25] program contained only full polarizations for the real photons. The polarization of virtual photons depends on the beam electric field $E_\omega^{x,y}$ at the point (x, y) where the pair is produced. For gaussian bunches an analytical expression has been derived [29] and can be solved by using the condition for flat beams $\sigma_x \gg \sigma_y$. The cross-section for the Breit-Wheeler process is also required with full polarizations. In CAIN this cross section σ^{circ} was written down only for the product of circular polarizations $\xi_2\xi_2'$ of initial photons k and k'. The full cross-section σ^{full} is a sum over all polarization states and functions of final electron energy ϵ and momentum p [30]. A numerical investigation of these two cross-sections reveals that the usual peak at low energies is substantially reduced when using the full cross-section for electron energies less than approximately 50 MeV. CAIN was modified with the above expressions and was run for all seven 500 GeV centre of mass collider parameter sets, cf. also [23]. There was a 10% to 20% overall reduction in pairs, with no discernible impact on collision luminosity [28].

The coherent production of pairs via the first order interaction between beamstrahlung photon and beam field is already included in CAIN. However the second order stimulated Breit-Wheeler process also takes place in the presence of the bunch fields. The cross-section calculation involves solutions of the Dirac equation in an external field. Naively, in comparison to the first order coherent process, the second-order cross-section should be diminished by an order of the fine structure constant. However the bunch field has the effect of allowing the second order cross-section to reach the on-shell mass. The resulting resonances are rendered finite by inclusion of the electron self-energy and the stimulated Breit-Wheeler cross-section can exceed the first order coherent process. A detailed theoretical and numerical investigation is required to gauge in detail the effect on produced pairs [26].

3.2. Spin transport

The SLICKTRACK [31] Monte Carlo computer code has been used to analyze the spin motion in the ILC damping ring (DR), main linac (ML) and beam delivery system (BDS). The simulation, applied for the 6km DR lattice at 5.0 GeV, shows that the sum of the mean squares of the angles of the tilts of spins away from the direction of the equilibrium polarization will be less than 0.1 mrad^2, even after 8 damping times. Also close to the spin-orbit resonance at 4.8 GeV the sum of the mean squares of the angles is only about 40 mrad^2, i.e. still negligible. In case a large energy spread was included in the simulation of about ± 25 MeV, much greater than the natural energy spread of the DR, the deviation was found to be 20 mrad^2, which is once again negligible [32].

A striking result is that the horizontal projections of the spin vectors of an e^- or e^+ bunch do not fully decohere, even after 8000 turns. In other words, if the spins are not perfectly oriented vertically at injection then their projections do not fan out uniformly in the horizontal plane during the damping [32]. SLICKTRACK has also been modified to simulate spin tracking in the ILC beam delivery system with an 2mrad crossing angle, including realistic misalignments. Consistent with [22] it was found that a depolarization of $< 0.06\%$ can be expected. Since the main linac in the current ILC design follows the Earth curvature, a spin precession of about 26 degrees is expected and the ratio between final and initial polarizations is about $\cos(10^{-4}\text{rad})$ [32].

4. Conclusions

Polarized beams are required to achieve many physics goals and to maximize the number of possible measurements at a collider facility, and are a basic ingredient for many present and future accelerator designs. The ILC provides already in the baseline a polarized e^- source with about $P_{e^-} = 80\% - 90\%$ and a polarized e^+ beam with about $P_{e^+} \sim 30\%$, extendable to at least $P_{e^+} \leq 60\%$, using undulator radiation to produce positrons. The scheme has been successfully tested at the E166 experiment and several undulator prototypes have been accomplished that already achieve the ILC requirements.

Precise spin tracking is a necessary condition for successfully applying polarized beams for physics. Much progress has been made describing spin motion during beam-beam interactions, in the damping ring, in the main linac and in the beam delivery system. Theoretical updates of the used calculations and the description of coherent and incoherent background processes including higher-order contributions have been accomplished. The analytically-based program CAIN has also been correspondingly updated.

With the code SLICKTRACK several simulations for different ILC lattices have been performed. They showed that only small depolarization can be expected at the ML. The depolarization in the BDS is small but not negligible. No full decoherence of horizontally spin components in the DR, however, can be expected. Proper alignment of the positron's spin directions prior to injection into the damping rings even for nominally unpolarized beams is therefore needed.

In order to guarantee that the produced polarization can be successfully utilized for physics analyses accurate polarimeters are needed. It has not yet been determined at what frequency the helicities of the beams have to be flipped between the possible polarization configurations in order to control systematic uncertainties on conditions at the IP. However, in order to fulfil both the high-luminosity as well as the high precision goals for physics analyses at the ILC, flipping of the helicities of the e^- beams as well as the e^+ beam is absolutely needed [10]. News on the positron source engineering design for the ILC and further polarization issues can be obtained from the working group of the ILC positron source group, see also [11].

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